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FUTURE PROSPECTS FOR MUON FACILITIES*

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The motivation, prospects, and R&D plans for future high–intensity muon facilities are described, with an emphasis on neutrino factories. The additional R&D needed for muon colliders is also considered.

1 Introduction

Recently there has been much interest in developing a very intense muon source capable of producing a millimole of muons per year. This interest is well motivated. A very bright muon beam that can be rapidly accelerated to high energies would provide a new tool for particle physics. The beam toolkit presently available to physicists interested in particle interactions at the highest energies is limited to beams of charged stable particles: electrons, positrons, protons, and antiprotons. The development of intense μ^+ and μ^- beams would significantly extend this toolkit, opening the way for multi-TeV muon colliders [1], lower energy muon colliders (Higgs factories [2]), muon–proton colliders, etc. In addition, all of the muons decay to produce neutrinos. A new breed of high energy high intensity neutrino beams would become possible [3]. Finally, there is the prospect of using the low energy (or stopped) muons to study rare processes with orders of magnitude more muons than currently available.

In response to the seductive vision of a millimole muon source an R&D collaboration was formed in the US in 1995, initially motivated by the desire to design a multi-TeV muon collider, and more recently by the desire to design a "neutrino factory" [3,4]. The motivation for neutrino factories is two-fold. First, the neutrino physics that could be pursued at a neutrino factory is compelling [5]. Second, a neutrino factory would provide a physics-driven project that would facilitate the development of millimole muon sources: the enabling technology for so many other goodies, including muon colliders.

[a]Presented at ICHEP2000, Osaka, Japan

2 The Neutrino Factory Concept

Conventional neutrino beams are produced from a beam of charged pions decaying in a long (typically several hundred meters) decay channel. If positive (negative) pions are selected, the result is an almost pure ν_μ ($\overline{\nu}_\mu$) beam from $\pi^+ \to \mu^+\nu_\mu$ ($\pi^- \to \mu^-\overline{\nu}_\mu$) decays. The neutrino oscillation physics community would like ν_e and $\overline{\nu}_e$ beams as well as ν_μ and $\overline{\nu}_\mu$ beams. For this we will need a different sort of neutrino source.

An obvious way to try to get ν_e and $\overline{\nu}_e$ beams is to exploit the decays $\mu^+ \to e^+\nu_e\overline{\nu}_\mu$ and $\mu^- \to e^-\nu_\mu\overline{\nu}_e$. To create a neutrino beam with sufficient intensity for a new generation of oscillation experiments will require a very intense muon source. With a millimole of muons per year we can imagine producing high energy beams containing O(10^{20}) neutrinos and antineutrinos per year. However, to achieve this a large fraction f of the muons must decay in a channel that points in the desired direction. Muons live 100 times longer than charged pions. Since the decay fraction f must be large we cannot use a linear muon decay channel unless we are prepared to build one that is tens of kilometers long. A more practical solution is to inject the muons into a storage ring with long straight sections. The useful decay fraction f is just the length of the straight section divided by the circumference of the ring. It has been shown that $f \sim 0.3$ is achievable [6]. The resulting muon

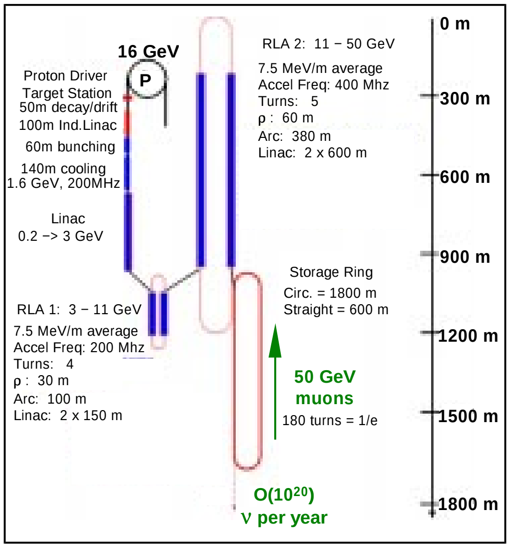

Figure 1. Schematic of the neutrino factory design from the 6 months feasibility study at Fermilab.

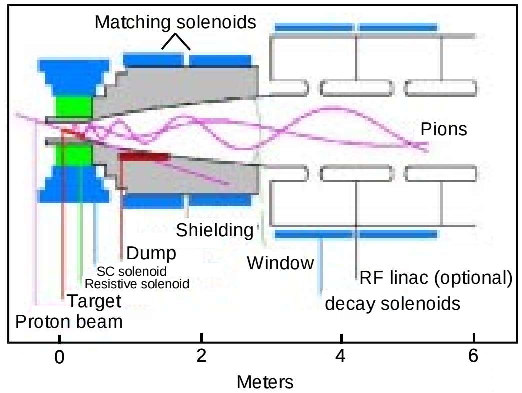

Figure 2. Conceptual layout of an intense pion source. The pion decay channel starts at 3 meters and continues for 50 meters to the right.

storage ring is sufficiently compact that it can be tilted downwards at a large angle so that the neutrino beam can pass through the Earth [3], and very long baseline experiments ($L \sim O(10^4)$ km) can be imagined.

Thus the "neutrino factory" concept [3,4], shown in Fig. 1, is to create a millimole/year muon source, rapidly accelerate the muons to the desired storage ring energy, and inject them into a storage ring with a long straight section that points in the desired direction.

3 Making Muons

Muons are produced in charged pion decays. Figure 2 shows a conceptual layout of the required pion source. The pion production target receives beam from a high–intensity multi–GeV proton driver. Most of the pions are produced with both longitudinal and transverse momenta of a few hundred MeV/c or less. These pions can be radially confined within a high–field solenoid. Therefore the target is within a 20 T solenoid, and is tilted at a small angle to reduce pion reabsorption. Downstream of the target solenoid the captured pions are transfered to a lower field larger radius solenoidal decay channel.

As an example, in the recent 6 months study [6] the design was based on a 16 GeV accelerator cycling at 15 Hz, and producing a 1.5 MW beam composed of 4×10^{13} protons/pulse, with each pulse consisting of 4 bunches separated by 500 ns. Detailed simulations predict 0.18 π^+/p and 0.15 π^-/p within the channel 9 m downstream of an 80 cm long carbon target tilted at 50 mrad, where the pions are required to have kinetic energies in the range 30–230 MeV. Hence, there are $\sim 10^{21}$ captured π^+ per 10^7 seconds of operation. If the pion source was upgraded to use a 4 MW proton beam incident on a liquid Hg jet target the pion yields increase by about a factor of 5.

The pions are produced with a large energy spread and small time spread (population A in Fig. 3). At the end of a 50 m long 1.25 T decay channel 95% of the pions have decayed. The daughter muons have a large energy spread, but their energies are correlated with their arrival time, with the faster muons arriving before the lower energy par-

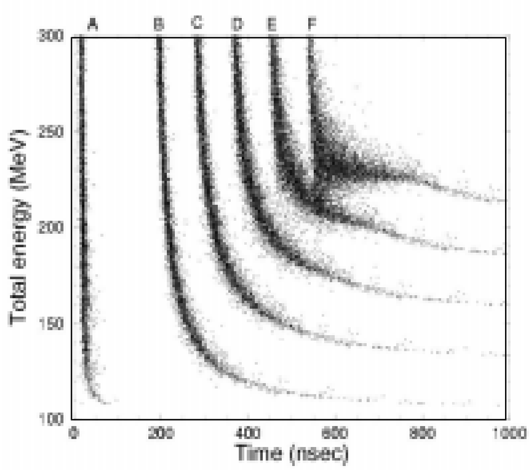

Figure 3. Simulated particle longitudinal phase–space populations: (A) pions at the production target, (B) Muons at the end of the decay channel, (C)–(F) Muons as they propagate down the induction linac.

ticles (population B in Fig. 3). Before we can capture the muons into RF bunches we must reduce their energy spread, which can be done either using RF cavities or using an induction linac to accelerate the late particles and deaccelerate the early particles.

In the induction linac design shown in Fig. 4 a 3 T superconducting solenoid channel (r = 20 cm) at the center of the linac keeps the muons radially confined. The linac consists of 100 modules, each 1 m long with a 10 cm gap providing a potential difference from -0.5 to +1.5 MV. A current pulse excites the induction cores outside of the solenoids. The changing toroidal magnetic field in the cores produces the accelerating gradient in the gap. The particle populations C–F in Fig. 3 show the evolution of the longitudinal phase–space occupied by the muons as they propagate down the linac.

After the energy spread has been reduced in the induction linac, the next task is to capture the muons with $E \sim 230$ MeV into a string of RF buckets. It is convenient to pass the muons through a 2.5 m long liquid hydrogen absorber, reducing their energy

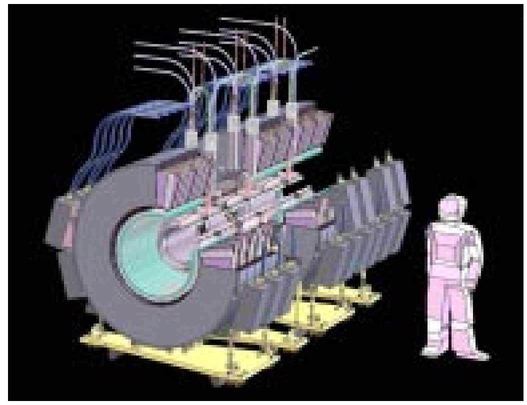

Figure 4. Induction linac design from the 6 months feasibility study at Fermilab.

by $\sim$ 80 MeV. The muons can then be captured into $\sim$ 50 bunches with a 200 MHz buncher. Detailed simulations predict that at this point there will be 0.12μ captured per proton on the pion production target. However, with the design used for the 6 months study the RF buckets are full, dooming us to substantial particle losses as the beam enters the cooling channel, which is the last component of the muon source. A better RF capture design is currently being studied.

4 Cooling Muons

Before the muons can be accelerated to high energies we must reduce their transverse phase-space so that they fit within the acceptance of the first acceleration stage. This means we must "cool" the transverse phase–space by at least a factor of a few in each transverse plane. This must be done fast, before the muons decay. Stochastic– and electron–cooling are too slow, so we will need to use a new cooling technique. The technique proposed is "ionization cooling". In an ionization cooling channel the muons pass through an absorber in which they lose transverse– and longitudinal–momentum by dE/dx losses. The longitudinal momentum is then replaced using an RF cavity, and the

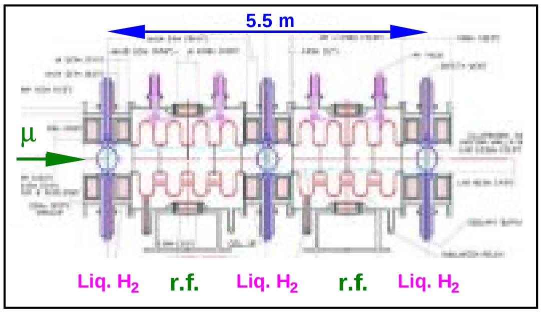

Figure 5. Cooling channel design.

process is repeated many times, removing the transverse muon momenta. This cooling process will compete with transverse heating due to Coulomb scattering. To minimize the effects of scattering we chose low–Z absorbers placed in the cooling channel lattice at positions of low–$\beta_\perp$ so that the typical radial focusing angle is large. If the focusing angle is much larger than the average scattering angle then scattering will not have much impact on the cooling process.

Figure 5 shows one design for a short section of an $\sim$ 100 m long cooling channel. To minimize scattering, liquid hydrogen absorbers are used with thin low–Z windows. The absorbers are located at low–$\beta_\perp$ locations within a high–field solenoid channel. The absorber sizes and the exact arrangement of solenoids vary with different cooling lattice designs. The channel shown in Fig. 5 has 30 cm long absorbers with a radius of 15 cm, within a 3.5 T axial field. The reaccelerating cavities operate at 200 MHz and provide a peak gradient of 15 MV/m. This deep RF bucket is needed to keep the large muon energy spread captured longitudinally, as well as providing the reacceleration.

The performance of the channel shown in Fig. 5 has been simulated. Results are shown in Fig. 6. Whilst the total number of muons decreases as the bunch travels down the channel, the number within the acceptance of the first acceleration stage increases by a factor of $\sim$ 5. Further optimization is in progress – there are lots of lattice variants to study !

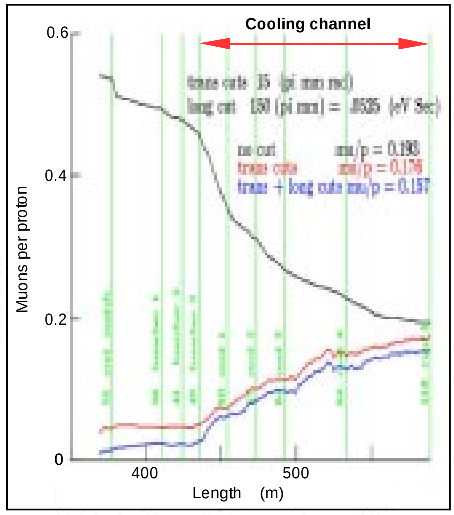

Figure 6. Simulated cooling channel performance. The total number of surviving muons (top curve) is shown versus position along the channel. The lower two curves show the number of muons within the acceptance of a large– and smaller–acceptance acceleration system. Lattice designed by R. Palmer.

5 Acceleration and Storage

The acceleration system is shown in Fig. 1. We need high gradients to accelerate the muons to high energy before they decay. An average gradient exceeding 5 MV/m is desirable (Fig. 7). After the first accelerating stage large solenoidal fields are no longer needed to confine the muons, and the desire for high gradients and an acceptable peak power leads us to choose superconducting RF. Once the muons have been accelerated to the desired energy, they are injected into a large acceptance storage ring with long straight sections ... and we are in business.

6 R&D

The goal for the 6 month feasibility study was to design a neutrino factory providing

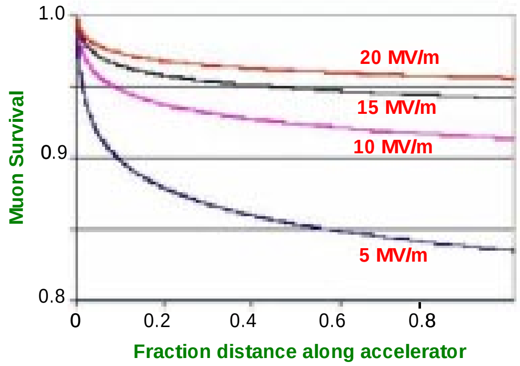

Figure 7. Muon survival as a function of distance along a 50 GeV acceleration system, shown for four different average accelerating gradients.

2×10^{20} muon decays per year in the beam–forming straight section. The study design yielded 6×10^{19} decays per year, not quite achieving the goal. With a more optimal RF buncher and cooling channel design and a slighter larger acceptance accelerator the design goal is probably achievable. With an upgraded 4 MW proton driver and a liquid Hg target an additional factor of 5 in intensity might be achieved. However, there are many R&D issues that must be addressed before a neutrino factory could be built. Below is a summary of the main issues and the R&D that is being pursued to address them.

6.1 Target Issues

A target experiment [7] is being prepared at BNL. The main goals of this endeavor are to (i) demonstrate a MW–level target in a 20T solenoid, (ii) measure pion and neutron yields to benchmark the simulation codes, and (iii) demonstrate the target lifetime in the high radiation environment. This activity is expected to proceed over the next 3 years. In addition there are particle production experiments (E910 at BNL, HARP at CERN, and a proposal P–907 at Fermilab) that are expected to benchmark the pion yields within the next couple of years.

6.2 Induction Linac Issues

The main issues are (i) can a suitable pulser system be built (4 pulses separated by 500 ns), and (ii) can the stray fields from the internal SC solenoid be kept low enough so that the inductive coils do not saturate. Within the neutrino factory/muon collider collaboration it is proposed to demonstrate the linac and pulser in the next few years.

6.3 Cooling Issues

The mission of the MUCOOL collaboration [8] is to design, prototype, and bench–test all cooling channel components, and eventually beam–test a cooling section. The component issues are (i) can sufficiently high gradient RF cavities be built and operated in the appropriate magnetic field and radiation environment, (ii) can liquid hydrogen absorbers with thin enough windows be built so that the dE/dx heating can be safely removed, and (iii) can the lattice solenoids be built to tolerance and be affordable? The MUCOOL collaboration has embarked on a design, prototyping, and testing program for all these components. This is expected to proceed over the next 3 years. Once the components have been developed the next step will be to build and bench test a cooling section to ensure all engineering issues have been resolved.

Detailed planning for the beam test phase must wait until the cooling channel design work is further along. In particular we must have a good quantitative understanding of how changes to the channel parameters effect the performance of the channel, and what the real issues are that need to be addressed by a muon beam experiment. We would hope that we will know enough to propose an experiment in about a year. The experiment is likely to be a large scale endeavor, and may be fertile ground for international collaboration. Whilst this is being worked out, the more modest MUSCAT experiment [9] is under way at TRIUMF to measure the scattering of low energy muons in various materials.

6.4 Acceleration Issues

The main R&D issue is whether superconducting RF cavities can be operated at 200 Mz (and perhaps 400 MHz) with sufficiently high gradients, using a practical power source. The neutrino factory/muon collider collaboration is planning to develop and test appropriate cavities. This activity will probably take more than 3 years.

6.5 Alternative Designs

There are two ongoing initiatives that could change the design details, and adjust the R&D described so far. First, a second generation design study has been launched at BNL with the participation of the neutrino factory/muon collider collaboration. Second, there is a parallel study being pursued at CERN [10] using similar design ideas but different technology choices. Finally, there is a Japanese initiative [11] which could radically change the design, in which $\sim$ 1 GeV/c pions are collected directly into a large acceptance accelerator (FFAG), and FFAGs do everything (no cooling etc).

7 A Final Word on Muon Colliders

Further R&D issues must be resolved to realize a muon collider, which needs brighter beams to obtain reasonable luminosity, and a cost effective high energy acceleration scheme. Perhaps the most challenging issue is that of cooling. To continue the cooling process beyond that needed for neutrino factories will require a further technology that enables the longitudinal phase–space occupied by the bunches to be reduced. It has been proposed to use "emittance exchange" in which some of the gain in the transverse phase–space is traded for a gain in longitudinal phase–space. Although concepts for emittance exchange exist, no practical realization has yet been worked out on paper. This is currently under active study, and is a make–or–break issue for muon colliders.

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References

1. "$\mu^+\mu^-$ Collider: A Feasibility Study", Muon Collider Collab., FERMILAB-Conf.-96/092.
2. Muon Collider Collab., *Phys. Rev. ST Accel. Beams* **2**, 081001 (1999).
3. S. Geer, *Phys. Rev.* **D57**, 6989 (1998).
4. An older idea, ascribed to Kushkarev, Wojcicki, and Collins, was to inject pions into a storage ring with straight–sections, the pions decay in situ to create a captured muon beam. The resulting neutrino beam intensity is several orders of magnitude less than obtained with the modern neutrino factory scheme.
5. S. Geer, hep-ph/0008155, *Comments on Nuclear and Particle Physics.*
6. N. Holtkamp and D. Finley (editors) "A feasibility study of a neutrino source based on a muon storage ring", Report to the Fermilab Directorate, FERMILAB-PUB-00-108-E, http://www.fnal.gov/projects/muon_collider/nu-factory/nu-factory.html
7. BNL E951, spokesperson K. McDonald.
8. MUCOOL Collab., spokesperson S. Geer
9. MUSCAT Collab., Spokespeople: R. Edgecock and K. Nagamine.
10. http://muonstoragerings.cern.ch/
11. Y. Kuno and Y. Mori, talks at NUFACT00, May 2000.